Research Report

Analysis of a Double-Paraboloidal Mirror System

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Abstract

An analysis of a double-paraboloidal mirror system, known as the "clam shell" device, is presented. It is evident from laboratory observations that the system produces real images which can be measured in both direction and distance. The derived system equation is

$$\frac{1}{v} - \frac{1}{u} = \frac{4 \cos^2 \alpha/2 - 3 \cos^4 \alpha/2}{f}$$

where u and v are the object and image distances, respectively, α, the angle of obliquity of the incident light, and f, the focal length of the mirrors.

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Analysis of a Double-Paraboloidal Mirror System

1. INTRODUCTION

The "clam shell,"[1] as an optical device, consists of two paraboloidal mirrors mounted face to face in such a manner that the vertex of one mirror falls at the focal point of the other and vice versa. If a parameter, called the aperture ratio, is defined as the rim diameter divided by the focal length, then, owing to the geometry of the parabola, any two paraboloidal mirrors of aperture ratio equal to $\sqrt{8}$ will satisfy the necessary conditions for a "clam shell" arrangement. The field of view for this optical system is limited to twice the arc-tangent $\sqrt{8}$ or 141°3'.

The inherent aberrations of the images formed by the system prompted an investigation of the geometrical optics of this device. The development of analysis proceeded by considering a cross section containing the axis of the system and any arbitrary object point so that only the angle of obliquity of the incident light need be considered.

2. DISCUSSION

The system equation for the "clam shell" has been derived by considering the parabolic cross section to be approximated by circles. Each of these circles has a radius equal to the radius of curvature of the parabola at the particular point being considered. The general equation for the radius of curvature, r_c, of the parabola, derived in Appendix 1, is $r_c = 2f \sec^3 \alpha/2$ where α is the polar coordinate angle and f, the focal length.

Each point Pi on the parabola has a given radius of curvature for each α. At each point Pi, the spherical mirror formula for axial or paraxial incident light may be used. The well-known spherical mirror formula is

$$\frac{1}{u} + \frac{1}{v} = \frac{2}{r} \tag{1}$$

where u and v are the object and image distances, respectively, and r the radius. For a spherical mirror, r is fixed but for a parabolic mirror $r = 2f \sec^3 \alpha/2$, and therefore, along the parabola, there will be a different equation for each value of α.

Consider the point P_1 shown in Figure 1. Along the normal to the parabola at P_1 lies the center of curvature, C_c, and the radius of curvature, r_c.
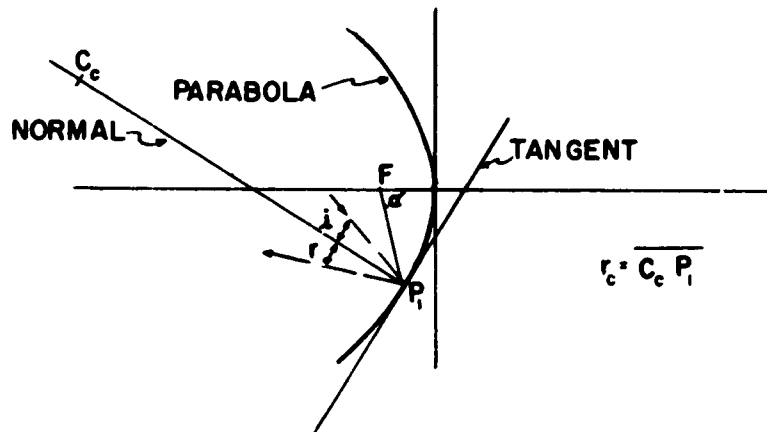
Figure 1. Parabola

The spherical mirror formula can be used for the portion of the parabolic mirror about P_1 as long as the incident light is axial (along the normal to point P_1), or not too far distant paraxially (parallel to the normal to P_1).

If the incident light falls obliquely on P_1 making an angle i with the normal and is reflected at an angle r=i, then the image produced will have the abberation called astigmatism. Astigmatism is the aberration of an optical system where two mutually perpendicular image positions are formed for a given object position.

The plane containing the chief ray and the axis, called the vertical plane, as shown in Figure 2 forms an image at the tangential image position, T, while the image at the sagittal image position, S, is formed by the plane, perpendicular to the vertical plane, containing the chief ray and intersecting the axis at an angle α.[2]

Figure 2. Astigmatic Image Formation by Oblique Rays

In the plane MVNQ, the reflected light converges along the chief ray to a point at T, while in the plane OVPQ, the convergence is at S. The plane MVNQ contains the axis and therefore is the plane in which the tangential image position appears. The sagittal image position lies in the plane O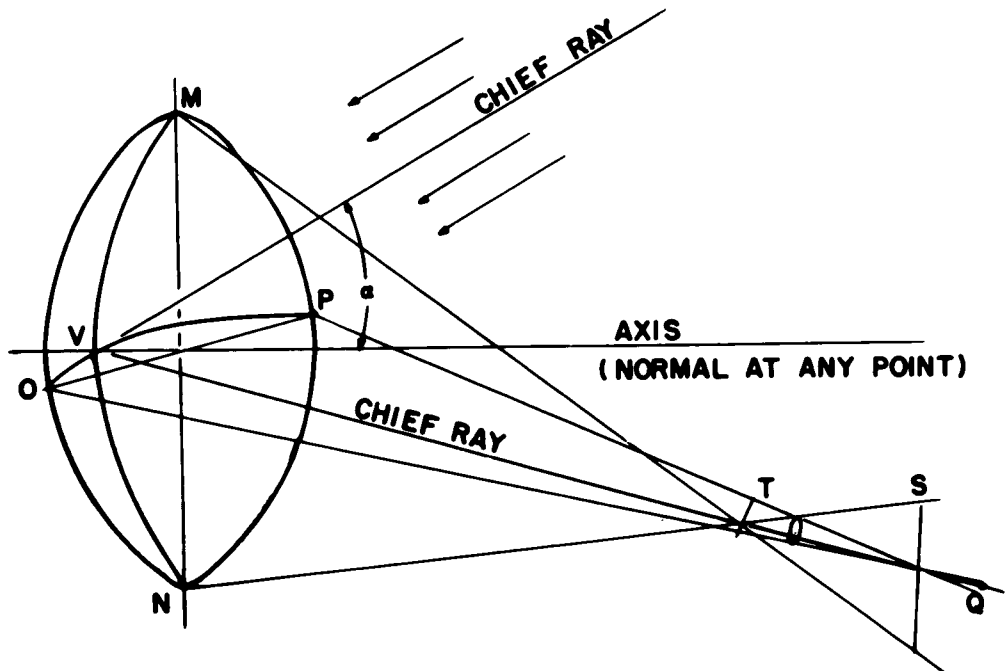VPQ, perpendicular to the plane MVNQ. An image is said to appear in a given plane if the light converges to a point in that plane. The images between S and T vary from straight lines to ellipses including a circle, called the circle of least confusion, where the major and minor axes of the ellipse are equal. When the foci of the sagittal and tangential image positions coincide there is no astigmatism.

The equations for the astigmatic image positions are derived in Appendix 2 for a spherical mirror:[3]

$$\frac{1}{u_1} + \frac{1}{v_{1t}} = \frac{2}{r \cos i} \tag{2}$$

$$\frac{1}{u_1} + \frac{1}{v_{1s}} = \frac{2 \cos i}{r} \tag{3}$$

where u_1 is the object distance, v_{1t} and v_{1s} are the tangential and sagittal image positions, respectively, measured along the chief ray; i is the angle of obliquity of the chief ray with the axis, and r is the radius of the sphere.

These two equations hold for any point Pi for a given angle i. If the restriction is held that $i = \alpha/2$, then, from the geometry of the parabola the incident light is constrained to pass through the focal point F and reflected parallel to the optical axis. The angle of the normal with respect to the axis will always be $\alpha/2$.

The restriction of allowing the incident light to enter the system only at the focal point has a direct relationship to the "clam shell" device where the apertures to the optical system are at the focal points of the mirrors.

The astigmatic image equations have been derived for spherical mirrors of radius r, but, in this application the mirrors are paraboloidal, parabolic in two dimensions and circular in the other. Consider the pictorial representation in Figure 3.[3]

The vertical planes AI'I''V, AK'K''V, etc., form the tangential image. Note that these planes section the mirror in parabolas. The planes AI'K', AI''K'', etc., form the sagittal image focus but the sections are circular. Therefore there will be a difference between the radius of curvature r_t for the tangential focus and the radius of curvature r_s for the sagittal focus in connection with a paraboloidal mirror.
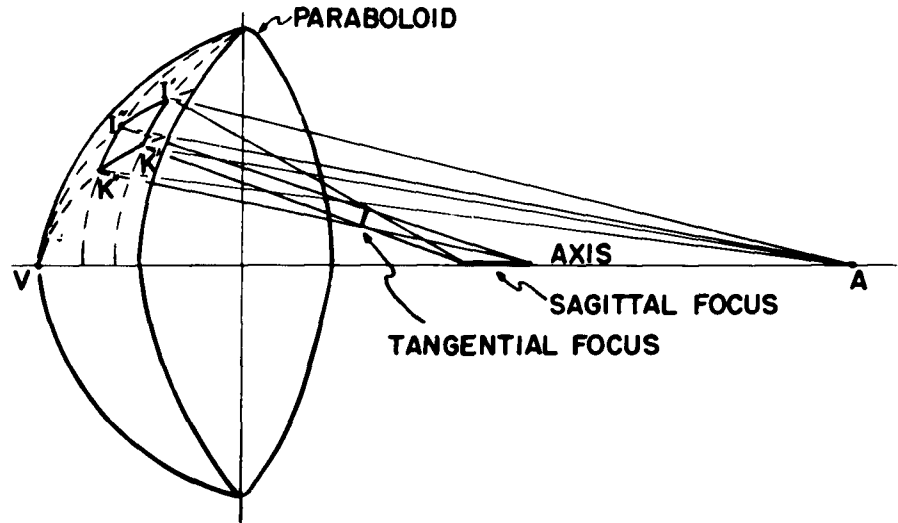
Figure 3.   Astigmatic Image Formation in Paraboloid

The normal at any point on the paraboloid will contain both the tangential and sagittal radii of curvature.   For the tangential radius, it can easily be seen that

$$r_t = 2f \sec^3 \alpha/2 \tag{4}$$

Since the sagittal sections are circular, their centers of curvature must be at the intersections of the normals to the parabola and the axis.   It is shown in Appendix 3 that

$$r_s = 2f \sec \alpha/2 \tag{5}$$

The astigmatic image equations will therefore reduce to

$$\frac{1}{u_1} + \frac{1}{v_{1t}} = \frac{2}{r_t \cos \alpha/2} = \frac{1}{f \sec^2 \alpha/2} \tag{6}$$

and

$$\frac{1}{u_1} + \frac{1}{v_{1s}} = \frac{2 \cos \alpha/2}{r_s} = \frac{1}{f \sec^2 \alpha/2} \tag{7}$$

The astigmatic image positions are equal under the restriction that the incident light pass through the focal point of one of the mirrors, as it does in the "clam shell" arrangement and thus there is no astigmatism presented by the system. The reflected light is parallel to the optical axis, becoming the incident light for a reflection at the second mirror.

The analysis regarding the sagittal and tangential image positions may also be applied to this second reflection with the same result that no astigmatism is introduced into the optical system. In this case, since the incident light is parallel to the axis, the reflected light will pass through the focal point of the second mirror.

The object distance u_2 for the second mirror will be equal to the image distance v_1 of the first reflection minus the horizontal distance d between the mirrors at the point of incidence. Since the image position of the first reflection falls behind the face of the second mirror, the object distance u_2 for the second mirror will be negative. It is shown in Appendix 4 that

$$d = f \left[\frac{4}{\sec \alpha + 1} - 1 \right] \tag{8}$$

and also that the total distance that the light travels from focal point to focal point inside the system is 3f.

The equations necessary for the second reflection are:

$$\frac{1}{u_2} + \frac{1}{v_2} = \frac{1}{f \sec^2 \alpha/2} \tag{9}$$

$$u_2 = - (v_1 - d). \tag{10}$$

It is therefore possible to solve the equations of both reflections to obtain v_2 in terms of u_1.

In applying the mirror equations to the "clam shell" arrangement, two conveniences are introduced to permit an easier evaluation of the final equation: (1) the distance u to the object is measured from the focal point of the first reflecting surface and (2) the final image position v is measured from the focal point of the second reflecting surface towards that surface.

As a consequence of these conveniences, the changes in the mirror equations and the derivation of the system equation proceed as shown in Figure 4.
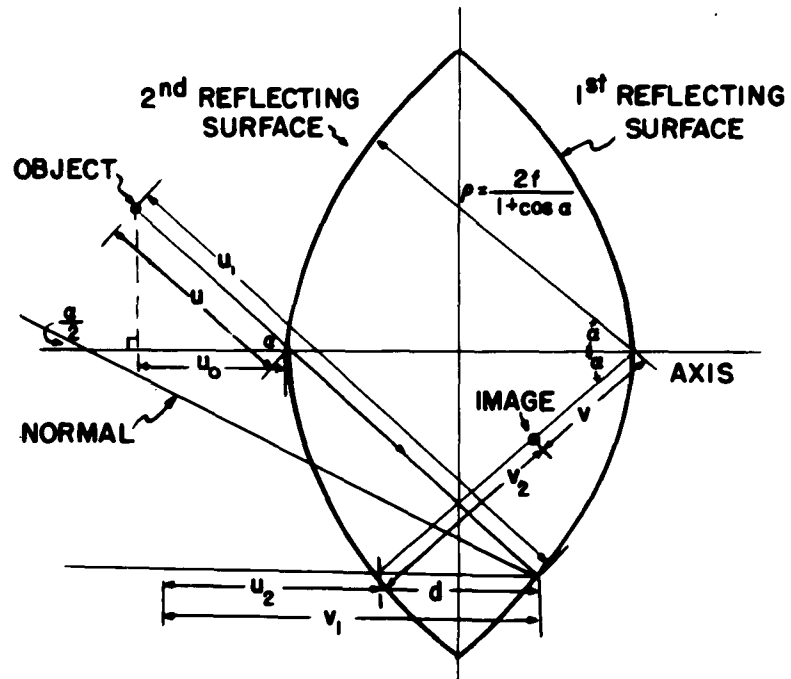

Figure 4. "Clam Shell" - Geometrical Cross Section

The position equations are:

$$\frac{1}{u_1} + \frac{1}{v_1} = \frac{1}{f \sec^2 \alpha/2} \tag{11}$$

$$\frac{1}{u_2} + \frac{1}{v_2} = \frac{1}{f \sec^2 \alpha/2} \tag{12}$$

$$u_1 = u + \frac{3f - d}{2} = u + \rho \tag{13}$$

$$u_2 = -(v_1 - d) \tag{14}$$

$$v = \frac{3f - d}{2} - v_2 = \rho - v_2 \tag{15}$$

Combining the five equations and solving for v in terms of u_1, one observes that the final system equation, completed in Appendix 5, is

$$\frac{1}{v} - \frac{1}{u} = \frac{4 \cos^2 \alpha/2 - 3 \cos^4 \alpha/2}{f}$$

As a detection device, the "clam shell" arrangement can readily yield an unknown object distance and direction once the image position and angle are measured. The only aberrations in the arrangement are astigmatism and curvature of field. In deriving the system equation, the effect of astigmatism has been overcome by permitting the incident light to enter the system only at the focal point of one of the mirrors. In practice, a pinhole aperture at the focal points is not realizable and as a result of an opening at the focal points an astigmatic image is produced. In detecting such an image, however, the position of least confusion represents the best image, which is relatively easy to locate. Astigmatism, therefore, depends upon the aperture of the system; its effects may be minimized by an appropriate opening.

Curvature of field is the aberration of an image whereby an object locus which is a straight line perpendicular to the axis results in an image locus which is curved. When astigmatism is present, the image locus will follow the position of the circle of least confusion, but, even for an assumed pinhole aperture in the "clam shell", curvature of field is apparent. To illustrate this effect, consider Figure 5 which is a plot of the angle of obliquity versus the image distance for object points lying on a straight line perpendicular to the axis. The calculated data for this figure appear in Table A of Appendix 6. From Figure 5, the effects of both angle and object distance upon image position and hence curvature of field can easily be seen. The ideal image positions are shown by the dashed lines. Knowledge of curvature of field is useful for photographic plates which must be fitted to the locus when used to focus a sharply defined image.

To investigate the effect of the angle of obliquity upon the image position with the object distance held constant, consider the curves of Figure 6. The calculated data for this figure appear in Table B of Appendix 6. These curves show how a spherical object or source is imaged by the "clam shell." Knowledge of this phenomenon is useful in describing the aberrations of an image as applied to thermal imaging techniques.
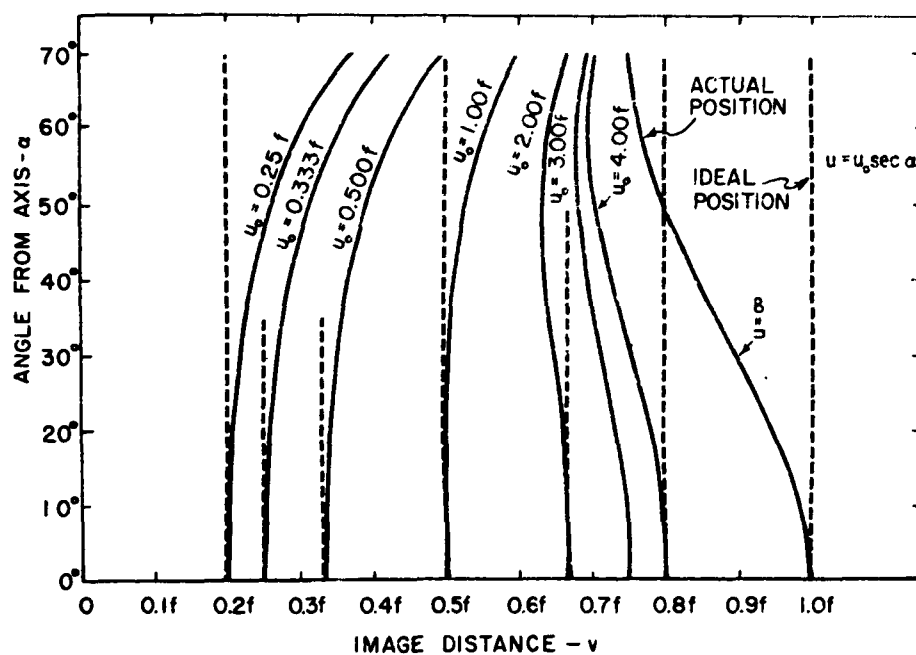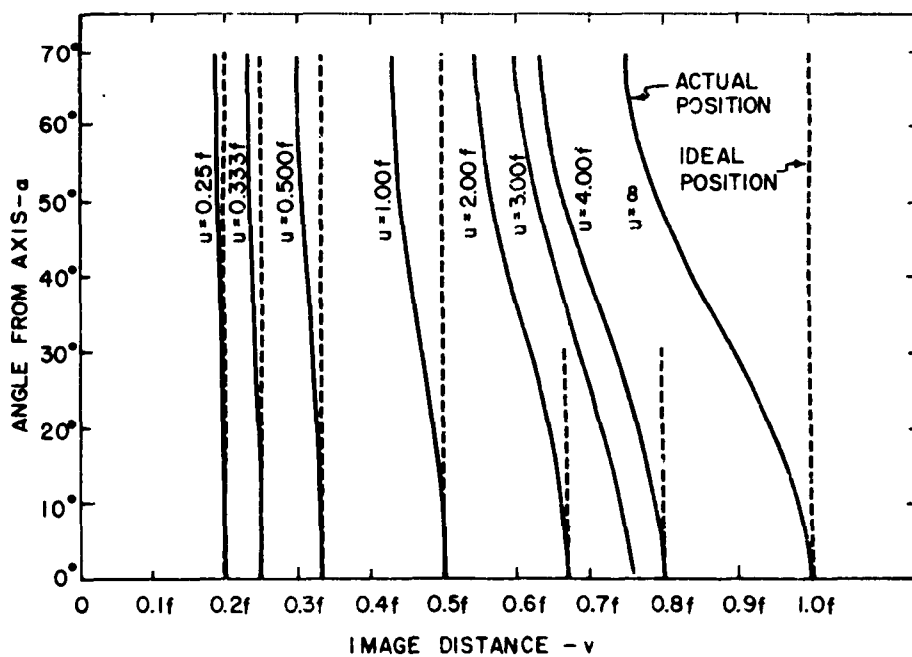
Figure 5. Curvature of Field

Figure 6. Curvature or Spherical Field

3. CONCLUSIONS

The optical system described in this report is capable of being used as a detection and range-finding device in accordance with the system equation. While no specific utilization of the "clam shell" as such a device is known, the possibility of such an application is not remote. Presently, the "clam shell" is used as a display device and as a thermal imaging device.

References

1. G. P. PLOETZ, "The 'Clam Shell' Thermal Image Device: Thermal Imager," September, 1959, AFCRC-TN-59-759.
2. F. A. JENKINS and H. E. WHITE, Fundamentals of Optics, McGraw-Hill Book Co., Inc., New York, 1957.
3. J. B. TOURRIOL, Optique Géométrique, Gauthier-Villars, ed. Libraire du Bureau des Longitudes, de L'ecole Polytechnique; Quai des Grands-Augustins, 55, 1951.

The equation of a parabola in Cartesian and polar coordinates may be represented by

$$y^2 = 4fx + 4f^2 = 2px + p^2$$

and

$$\rho = 2f(1 + \cos \alpha)^{-1}, \text{ respectively.}$$

In Cartesian coordinates, curvature K is given by

$$K = \frac{y''}{(1 + y'^2)^{3/2}} :$$

$$y'^2 = \left[\frac{p}{y}\right]^2 = \left[\frac{2f}{\rho \sin \alpha}\right]^2 = ctn^2 \alpha/2$$

$$y'' = \frac{-p^2}{y^3} = \frac{-1}{y} ctn^2 \alpha/2$$

$$K = -\frac{ctn^2 \alpha/2}{y(1 + ctn^2 \alpha/2)^{3/2}} = -\frac{ctn^3 \alpha/2}{p(1 + ctn^2 \alpha/2)^{3/2}} = -\frac{ctn^3 \alpha/2}{p \csc^3 \alpha/2}$$

$$K = -\frac{\cos^3 \alpha/2}{p}$$

The radius of curvature r_c is given by the reciprocal of the curvature and therefore

$$r_c = -2f \sec^3 \alpha/2.$$

The negative sign denotes a concave downward curve, but only the magnitude of the radius of curvature need be considered here.
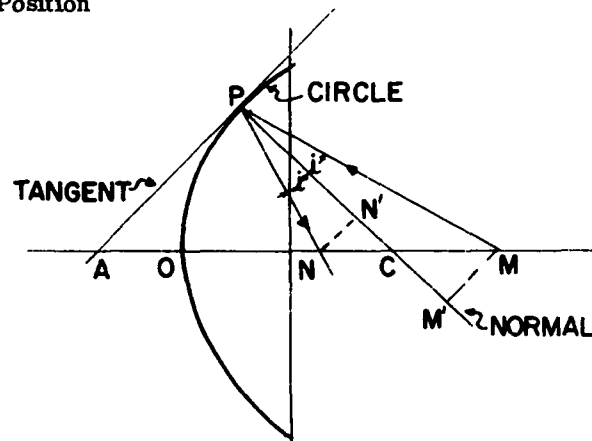
Sagittal Image Position

Figure 2-1 Sagittal Image Formation

Let N be a point on the sagittal focus corresponding to incident light along the path MP. The points M, N, O, and A form an harmonic division and therefore

$$\frac{1}{AM} + \frac{1}{AN} = \frac{2}{AC}.$$

Projection of the distances AM, AN, and AC on the normal yields

$$\frac{1}{PM'} + \frac{1}{PN'} = \frac{2}{PC}.$$

Now, PM' = PM cos i and PN' = PN cos i.
Therefore

$$\frac{1}{PM} + \frac{1}{PN} = \frac{2 \cos i}{PC} \ .$$

Denoting PM and PN as the object and image distances, respectively, one can easily see that PC is the radius of curvature of the curve at point P.
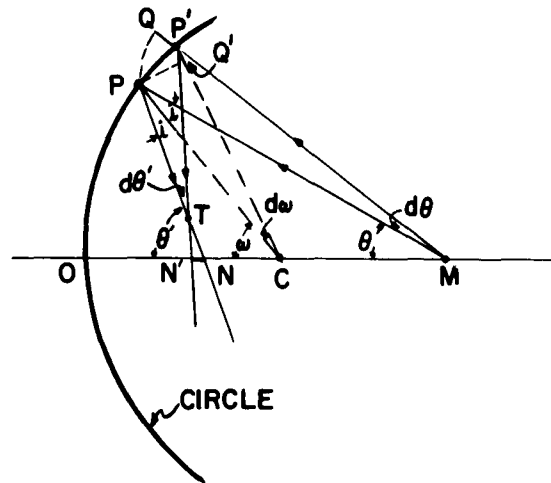
Tangential Image Position

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Figure 2-2 Tangential Image Formation

In the triangle CPM,
$\omega = \theta' + i$; and in the triangle
CPN, $\omega = \theta' - i$. Therefore

$$2\omega = \theta + \theta'$$

and differentiating yields

$$2d\omega = d\theta + d\theta'.$$

Now, with PC as a radius,
construct an arc such that
PP' = PC dω. With PM as
a radius, construct the arc

PQ = PM dθ and since angle QPP' = angle i, then PQ = PP' cos i, and therefore
PM dθ = PP' cos i.

With PT as a radius, construct the arc PQ', and as before, PT dθ' = PP'
cos i, since angle Q'PP' = angle i.

Substituting for dω, dθ, and dθ' yields

$$2 \frac{PP'}{PC} = \frac{PP'}{PM} \cos i + \frac{PP'}{PT} \cos i$$

or

$$\frac{2}{PC \cos i} = \frac{1}{PM} + \frac{1}{PT}$$

If PM and PT are the object and images, respectively, PC will be the radius
of curvature of the curve at point P.

It should be noted that the line NN', the sagittal focal position locus, is per-
pendicular to the line going through the point T into the paper. This latter line
is the locus of the tangential focal positions.

The derivations of the sagittal and tangential image position equations assumed
a spherical mirror as the reflecting surface.

SAGITTAL AND TANGENTIAL CURVATURES
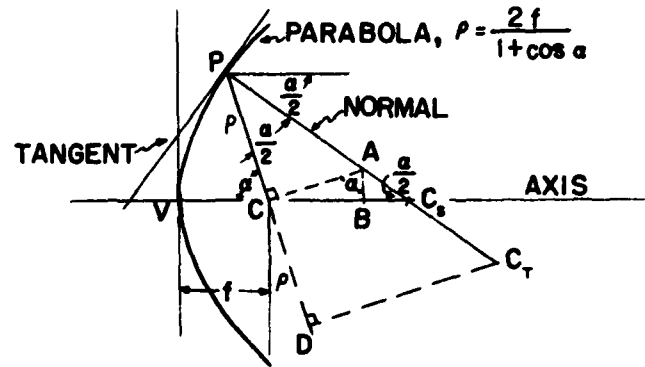
Figure 3-1 Radii of Curvature for Paraboloid

The above construction on the parabola at any point P yields:

$$PA = \rho \ \sec \alpha/2; \ PC_T = 2\rho \ \sec \alpha/2$$

$$CA = \rho \ \tan \alpha/2; \ DC_T = 2\rho \ \tan \alpha/2$$

$$AC_s = \frac{AB}{\sin \alpha/2} = \frac{\rho \ \tan \alpha/2 \ \cos \alpha}{\sin \alpha/2} = \rho \ \frac{\cos \alpha}{\cos \alpha/2} \cdot$$

Therefore, the tangential radius of curvature r_T is given by

$$r_T = PC_T = 2f \ \sec^3 \alpha/2.$$

The sagittal radius of curvature r_s is given by

$$r_s = PA + AC_s = \rho \ \sec \alpha/2 + \rho \ \cos \alpha \ \sec \alpha/2$$

$$r_s = 2f \ \sec \alpha/2.$$

HORIZONTAL OPTICAL PATH IN "CLAM SHELL"

Figure 4-1 Internal Optical Path for "Clam Shell"

In calculating the horizontal distance d between the mirrors at points P_1 and P_2, the equations of the parabolas are given in Cartesian coordinates. P_1 lies on curve $y^2 = -4fx$ and P_2 lies on $y^2 = 4fx + 4f^2$.

$$d = x_1 - x_2$$

$$= -\frac{y^2}{4f} - \left[\frac{y^2}{4f} - f\right] = f - 1/2\frac{y^2}{f} .$$

The equation of the line FP_1 is

$$y = - x \tan \alpha - f \tan \alpha$$

At P_1, $y^2 = -4fx$; therefore substituting for x from the equation of FP_1 yields

$$y^2 - 4fy \operatorname{ctn} \alpha - 4f^2 = 0$$

or

$$y = 2f \operatorname{ctn} \alpha(1 \pm \sec \alpha)$$

Due to the construction of the "clam shell" $\tan \alpha \leq 2\sqrt{2}$ and $\sec \alpha \geq 1$.

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Therefore

$$y = 2f \ ctn \ \alpha(1 - sec \ \alpha).$$

Therefore, solving for d gives

$$d = f - \frac{4f^2}{2f \tan^2 \alpha} (1 - sec \ \alpha)^2 = f\left[1 - \frac{2(1 - sec \ \alpha)^2}{\tan^2 \alpha}\right]$$

which may be reduced to

$$d = f\left[\frac{4}{sec \ \alpha + 1} - 1\right].$$

It is interesting to note that when $\alpha = 0$, then $d = f$ which is the distance between vertices of the mirrors. Also, when α is maximum or $\tan \alpha = 2\ 2$ and $sec \ \alpha = 3$, then $d = 0$ as it does when the mirrors are together.

The total light path from focal point to focal point in the "clam shell" is $2\rho + d$ which equals $3f$. In computing this distance, only magnitudes are of importance and therefore the total distance d_T is given by

$$d_T = 2 \ \frac{2f}{1 + cos \ \alpha} + \frac{4f}{sec \ \alpha + 1} - f$$

$$= \frac{4f}{1 + cos \ \alpha} + \frac{4f \ cos \ \alpha}{1 + cos \ \alpha} - f = 3f$$

From the geometry of the "clam shell," it can easily be seen that for light incident at the maximum angle, $\tan \alpha = 2\sqrt{2}$, that $\rho = 3/2 \ f$ and $d = 0$. Therefore $d_T = 3f$.

Appendix 5
DERIVATION OF THE SYSTEM EQUATION

$$\frac{1}{u^*} + \frac{1}{v^*} = \frac{1}{f \sec^2 \alpha/2} \tag{1}$$

$$\frac{1}{u_2} + \frac{1}{v_2} = \frac{1}{f \sec^2 \alpha/2} \tag{2}$$

$$u^* = u + \rho \tag{3}$$

where

$$\rho = \frac{2f}{1 + \cos \alpha} = f \sec^2 \alpha/2$$

$$u_2 = - (v^* - d) \tag{4}$$

where

$$d = 3f - 2\rho$$

$$v = \rho - v_2 .$$

Solving for v^* in terms of u, using Eqs. (1) and (3) yields

$$\frac{1}{v^*} = \frac{1}{f \sec^2 \alpha/2} - \frac{1}{u + \rho} \tag{5}$$

$$v^* = \frac{(u + \rho) \, f \sec^2 \alpha/2}{u + \rho - f \sec^2 \alpha/2} = \frac{(u + \rho)\rho}{u}. \tag{6}$$

Solving for v_2 in terms of v^*, using Eqs. (2) and (4) yields

$$\frac{1}{v_2} = \frac{1}{f \sec^2 \alpha/2} - \frac{-1}{v^* - d}$$

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and

(7)

$$v_2 = \frac{(v'' - d)\rho}{v'' - d + \rho} \ .$$

Eliminating v'' from Eqs. (5) and (7) yields

$$v_2 = \frac{3u\rho^2 + \rho^3 - 3f\rho u}{4u\rho + \rho^2 - 3fu} \ . \tag{8}$$

Using Eq. (5) and solving for v in terms of u yields

$$v = \rho - \frac{3u\rho^2 + \rho^3 - 3f\rho u}{4u\rho + \rho^2 - 3fu}$$

$$= \frac{4u\rho^2 + \rho^3 - 3f\rho u - 3u\rho^2 - \rho^3 + 3f\rho u}{4u\rho + \rho^2 - 3fu}$$

$$= \frac{u\rho^2}{4u\rho + \rho^2 - 3fu}$$

$$= \frac{uf^2 \sec^4 \alpha/2}{4uf \sec^2 \alpha/2 + f^2 \sec^4 \alpha/2 - 3fu} \ . \tag{9}$$

Therefore

$$v = \frac{uf}{f + u(4 \cos^2 \alpha/2 - 3 \cos^4 \alpha/2} \tag{10}$$

or

$$\frac{1}{v} - \frac{1}{u} = \frac{4 \cos^2 \alpha/2 - 3 \cos^4 \alpha/2}{f} \ .$$

Appendix 6

TABLE A. Calculations for Curvature of Field

sec α	u_o 0.250f	0.333f	0.500f	1.00f	2.00f	3.00f	4.00f	∞
3	0.375f	0.429f	0.500f	0.600f	0.667f	0.692f	0.705f	0.750f
5/2	0.342f	0.395f	0.469f	0.578f	0.660f	0.684f	0.699f	0.752f
11/5	0.318f	0.372f	0.458f	0.563f	0.646f	0.678f	0.696f	0.756f
2	0.302f	0.356f	0.432f	0.552f	0.640f	0.675f	0.695f	0.762f
13/7	0.289f	0.343f	0.420f	0.543f	0.636f	0.675f	0.696f	0.768f
5/3	0.272f	0.385f	0.403f	0.532f	0.632f	0.675f	0.695f	0.781f
3/2	0.255f	0.308f	0.387f	0.522f	0.632f	0.678f	0.706f	0.800f
7/5	0.245f	0.297f	0.377f	0.516f	0.632f	0.684f	0.712f	0.817f
9/7	0.241f	0.284f	0.364f	0.509f	0.636f	0.692f	0.734f	0.844f
11/9	0.226f	0.277f	0.358f	0.506f	0.638f	0.699f	0.734f	0.864f
12/11	0.210f	0.261f	0.343f	0.501f	0.652f	0.723f	0.764f	0.928f
1	0.200f	0.250f	0.333f	0.500f	0.667f	0.750f	0.800f	1.000f

$$\frac{1}{v} - \frac{1}{u} = \frac{4 \cos^2 \alpha/2 - 3 \cos^4 \alpha/2}{f}.$$

The locus of the object distance u is a straight line perpendicular to the axis. The on-axis projection of u is u_o and therefore $u = u_o \sec \alpha$. (See Figure 4.)

TABLE B. Calculations for Spherical Fields

sec α	u 0.250f	0.333f	0.500f	1.00f	2.00f	3.00f	4.00f	∞
3	0.187f	0.231f	0.300f	0.428f	0.545f	0.600f	0.632f	0.750f
5/2	0.187f	0.231f	0.300f	0.429f	0.546f	0.601f	0.633f	0.752f
11/5	0.188f	0.231f	0.301f	0.430f	0.549f	0.604f	0.636f	0.756f
2	0.188f	0.232f	0.302f	0.432f	0.552f	0.607f	0.640f	0.762f
13/7	0.189f	0.232f	0.303f	0.434f	0.555f	0.612f	0.645f	0.768f
5/3	0.189f	0.234f	0.305f	0.438f	0.562f	0.619f	0.653f	0.781f
3/2	0.190f	0.235f	0.308f	0.444f	0.571f	0.632f	0.666f	0.800f
7/5	0.191f	0.237f	0.310f	0.449f	0.579f	0.641f	0.678f	0.817f
9/7	0.193f	0.239f	0.314f	0.457f	0.593f	0.650f	0.696f	0.844f
11/9	0.194f	0.241f	0.317f	0.463f	0.603f	0.670f	0.712f	0.864f
12/11	0.197f	0.245f	0.325f	0.481f	0.634f	0.705f	0.753f	0.928f
1	0.200f	0.250f	0.333f	0.500f	0.666f	0.750f	0.800f	1.000f

$$\frac{1}{v} - \frac{1}{u} = \frac{4 \cos^2 \alpha/2 - 3 \cos^4 \alpha/2}{f}.$$

The locus of the object distance u is a circle. Therefore the table shows the variation in the image position with angle as u held constant.

UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass.
ANALYSIS OF A DOUBLE-PARABOLOIDAL MIRROR SYSTEM, by Denis M. Coffey. June 1963.
21 pp. incl. illus. tables. AFCRL-63-128
Unclassified report

An analysis of a double-paraboloidal mirror system, known as the "clam shell" device, is presented. It is evident from laboratory observations that the system produces real images which can be measured in both direction and distance. The derived system equation is

$$\frac{1}{v} - \frac{1}{u} = \frac{4\cos^2 \alpha/2 - 3\cos^4 \alpha/2}{f}$$

where u and v are the object and image distances, respectively, α, the angle of obliquity of the incident light, and f, the focal length of the mirrors.

1. Geometrical optics
2. Reflection
3. Image formation

I. Coffey, Denis M.

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AF Cambridge Research Laboratories, Bedford, Mass.
ANALYSIS OF A DOUBLE-PARABOLOIDAL MIRROR SYSTEM, by Denis M. Coffey. June 1963.
21 pp. incl. illus. tables. AFCRL-63-128
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